CHAPTER 5

MAGNETIC FIELDS IN MATTER

5.1 INTRODUCTION

The main objective of this chapter is to provide detailed concepts of magnetic behaviour in matter. The include:

- Magnetic force on moving charge, current element, and between two current elements.
- Lorentz force equation that describes the net force on a moving charge in presence of both electric and magnetic forces.
- Magnetic dipole moment and magnetic torque.
- Magnetic boundary conditions that relates the tangential and normal components of magnetic field.
- Magnetic characteristic of materials: magnetization, magnetic susceptibility, permeability.
- Types of magnetic materials: paramagnetic, diamagnetic, ferromagnetic.
- Energy stored in magnetic field and inductors.
- Analogy between electric and magnetic circuits.

5.2 MAGNETIC FORCES

Magnetic force is exerted by a magnetic field on charged particles, current elements, and current loops. These magnetic forces are discussed in following sections:

5.2.1 Force on a Moving Point Charge in Magnetic Field

If we allow a charge Q to move with a velocity $\boldsymbol{u}$ in the presence of a magnetic field, $\boldsymbol{B}$, then the magnetic force $\boldsymbol{F}_m$ exerted on the charged particle is given by

$$\boldsymbol{F}_m = Q(\boldsymbol{u} \times \boldsymbol{B}) \qquad ...(5.1)$$

Lorentz Force Equation

Since, the electric force $\boldsymbol{F}_e$ on a stationary or moving electric charge Q in an electric field $\boldsymbol{E}$ is given by

$$\boldsymbol{F}_e = Q\boldsymbol{E} \qquad ...(5.2)$$

So, from equations (5.1) and (5.2), the total force experienced by a moving charge in the presence of both the electric as well as the magnetic field is given as

$$\begin{aligned}\boldsymbol{F} &= \boldsymbol{F}_e + \boldsymbol{F}_m \\ &= Q\boldsymbol{E} + Q(\boldsymbol{u} \times \boldsymbol{B})\end{aligned}$$

This equation is known as *Lorentz force equation*. The comparison of the two forces (electric and magnetic forces) experienced by a moving charge has been summarized in the table below:

Table 5.1: Comparison between Electric Force and Magnetic Force

	Electric force ($F_e = QE$)	Magnetic Force ($F_m = Qu \times B$)
1.	It is in the same direction as the field E.	It is perpendicular to both u and B.
2.	It can perform work.	It cannot perform work.
3.	It is independent of the velocity of charge.	It depends upon the velocity of charge.
4.	It can produce change in kinetic energy.	It cannot produce change in kinetic energy.

5.2.2 Force on a Differential Current Element in Magnetic Field

The differential magnetic force experienced by various differential current elements are given below.

$$F_m = \int_L IdL \times B \qquad \text{(Line current)}$$

$$F_m = \int_S K \times B\, dS \qquad \text{(Surface current)}$$

$$F_m = \int_v J \times B dv \qquad \text{(Volume current)}$$

where IdL is the line current element, KdS is surface current element, Jdv is volume current element, and F_m is the magnetic force exerted on the respective elements in presence of magnetic field B.

5.2.3 Force on a Straight Current Carrying Conductor in Magnetic Field

From above discussion, we can say that if a conductor of length L carrying a current I is situated in uniform magnetic field B, it would experience a force given by

$$F_m = IL \times B$$

or,

$$F_m = BIL \sin\theta$$

where θ is the angle between the vectors B and L.

5.2.4 Magnetic Force Between Two Current Elements

Consider the two differential current elements $I_1 dL_1$ and $I_2 dL_2$ separated by a distance r. The magnetic force between the two current elements is given by

$$F = \frac{\mu I_1 I_2}{4\pi} \int_{L_2} \int_{L_1} \frac{dL_2 \times (dL_1 \times a_r)}{r^2}$$

This equation is also called *Ampere's force law.*

5.2.5 Magnetic Force Between Two Current Carrying Wires

Consider the two straight, long and parallel wires separated by a distance R as shown in Figure 5.1. Wire(1) carries current I_1 and wire(2) carries current I_2. The force exerted by wire(1) at wire(2) is given by

$$F_2 = \frac{\mu_0 I_1 I_2}{2\pi R}(-a_y)$$

Similarly, the magnetic force exerted by wire(2) at wire(1) is given by

$$F_1 = \frac{\mu_0 I_1 I_2}{2\pi R} a_y$$

Thus we conclude that there is a force of attraction between the two wires carrying currents in the same direction, i.e.

$$|F_1| = \frac{\mu_0 I_1 I_2}{2\pi R} = |F_2|$$

and

$$F_1 = -F_2$$

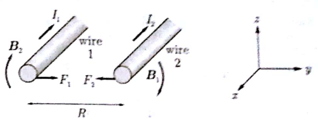

Figure 5.1: Magnetic Force between Two Current Carrying Wires

5.3 MAGNETIC DIPOLE

A magnetic dipole is created when a negative magnetic charge $-Q_m$ and a positive magnetic charge Q_m are placed at a small separation l. A bar magnet or a small filamentary loop carrying a current is known as a magnetic dipole. Figure 5.2 shows a bar magnet and its equivalent current loop.

Magnetic Dipole Moment of Bar Magnet

The magnetic dipole moment of the bar magnet is a vector quantity directed from $-Q_m$ to $+Q_m$. It is denoted by m and giverr as

$$m = Q_m l$$

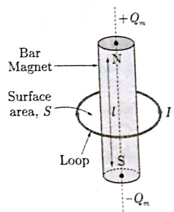

Figure 5.2 : Dipole Moment of a Bar Magnet and its Equivalent Current Loop

Magnetic Dipole Moment of Current Loop

If a magnetic dipole is linked to a current loop with area S and carrying current I as shown in Figure 5.2, then that loop has a magnetic dipole moment

$$m = IS = ISa_n$$

where, a_n is the unit vector normal to the plane of the loop and its direction is determined by the right-hand rule.

Magnetic Dipole Moment of Current Carrying Coil

If a coil has N turns (i.e., N loops), the net magnetic moment of the coil is given by

$$m = NIS$$

5.4 MAGNETIC TORQUE

When a current loop is placed parallel to a magnetic field, forces act on the loop, that tend to rotate it. The tangential forces times a radial distance at which it acts is called the torque or mechanical moment, on the loop. Mathematically,

$$T = d \times F$$

where F is the force acting on the loop and d is the moment-arm (i.e., radial distance of the force from axis of rotation). Torque is expressed in Newton-metres. It is a vector directed along the axis of rotation of the loop.

5.4.1 Torque in Terms of Magnetic Dipole Moment

If the magnetic moment is regarded as a vector m with direction normal to the plane of the loop; the torque relation can be expressed in a more general form using vector product. i.e.,

$$T = m \times B$$

where, T = Torque on loop (Nm)

$m = ma_m$ = magnetic moment of loop (Am^2)

B = flux density, Wb/m^2

5.5 MAGNETIZATION IN MATERIALS

Magnetization is defined as the amount of magnetic moment per unit volume. It is also called magnetic polarisation density. It is a vector quantity and denoted by (M). Its unit is Ampere per metre (A/m). If there are N atoms in a given volume Δv with magnetic moments $m_1, m_2, m_3, \ldots m_N$ respectively, then magnetization is given by

$$M = \lim_{\Delta v \to 0}\left(\frac{1}{\Delta v}\sum_{i=1}^{N} m_i\right)$$

5.5.1 Magnetic Susceptibility

In a linear material, magnetization is directly proportional to field intensity. i.e.

$$M \propto H$$

or,
$$M = \chi_m H$$

where χ_m is the magnetic susceptibility of the medium. The *magnetic susceptibility* of a magnetic material is a measure of the degree of magnetization of a material in response to an applied magnetic field.

5.5.2 Relation between Magnetic Field Intensity and Magnetic Flux Density

In a magnetic material, magnetic flux density is expressed in terms of magnetic field intensity as

$$B = \mu_0(H + M) = \mu_0(1 + \chi_m)H$$
$$= \mu_0\mu_r H = \mu H$$

where,

$\mu = \mu_0\mu_r$ is called permeability of the medium, expressed in Henry per metre (H/m),

$\mu_0 = 4\pi \times 10^{-7}$H/m is the permeability of free space, known as absolute permeability,

$\mu_r = (1 + \chi_m) = \frac{\mu}{\mu_0}$ is the relative permeability of the medium, it is dimensionless.

5.5.3 Classification of Magnetic Materials

Depending upon the values of the magnetic susceptibility (χ_m) or the relative permeability (μ_r), magnetic materials are broadly classified into three groups as

1. Paramagnetic materials
2. Diamagnetic materials, and
3. Ferromagnetic materials.

Paramagnetics and diamagnetics are linear magnetic materials whereas ferromagnetics are non linear materials. The characteristics of these magnetic materials are given in Table 5.2.

5.6 MAGNETOSTATIC BOUNDARY CONDITIONS

Magnetic boundary conditions are the conditions that B or H or M field must satisfy at the boundary between two different magnetic media. In the following sections, the boundary relationships are described separately for the field components normal to the boundary and tangential to the boundary.

5.6.1 Boundary condition for the normal components

Consider the normal components of magnetic field shown in Figure 5.3. The two different magnetic media 1 and 2 are characterised by the permeabilities μ_1 and μ_2 respectively. From the boundary condition, the normal components of magnetic field are related as

$$B_{1n} = B_{2n}$$

In terms of the field intensity, the boundary condition can be written as

$$\mu_1 H_{1n} = \mu_2 H_{2n}$$

Thus, the normal component of B is continuous, but normal component of H is discontinuous at the boundary surface.

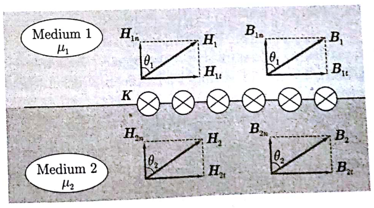

Figure 5.3: Magnetic Boundary Conditions

Table 5.2: Classification of Magnetic Materials

S.N.	Paramagnetic	Diamagnetic	Ferromagnetic
1.	The atoms or molecules have a permanent magnetic dipole moment.	The magnetic material does not have permanent magnetic dipoles.	Ferromagnetic materials are made up of small patches called magnetic domains.
2.	In the absence of any applied external magnetic field, the permanent magnetic dipoles in a paramagnetic material are randomly aligned and thus do not have any magnetization ($M = 0$) and thus, the average magnetic field (B_i) is also zero.	The presence of an external field B_0 will induce magnetic dipole moments in the atoms or molecules. However, these induced magnetic dipoles are anti-parallel to B_0, leading to a magnetization M and average field anti-parallel to B_0, and therefore, a reduction in the total magnetic field strength	An externally applied field B_0 will tend to line up those magnetic dipoles parallel to the external field. The strong interaction between neighbouring atomic dipole moments causes a much stronger alignment of the magnetic dipoles than in paramagnetic materials.
3.	When placed in an external field ($\boldsymbol{H}$), the dipoles experience a torque that tends to align $\boldsymbol{m}$ with $\boldsymbol{H}$, thereby producing a net magnetization ($\boldsymbol{M}$) parallel to $\boldsymbol{H}$. Since $\boldsymbol{B}_i$ is parallel to $\boldsymbol{H}$, it will tend to enhance the field.		The enhancement of the applied external field can be considerable, with the total magnetic field inside a ferromagnet 10^3 or 10^4 times greater than the applied field.
4.	The magnetization ($\boldsymbol{M}$) is not only in the same direction as ($\boldsymbol{H}$), but also linearly proportional to it.		
5.	Paramagnetism is temperature dependent.		
6.	$\mu_r > 1$, $\chi_m > 0$ (In paramagnetics χ_m is usually of the order of 10^{-6} to 10^{-3}.)	$\mu_r < 1$, $\chi_m < 0$ (In diamagnetics χ_m is usually of the order of -10^{-5} to -10^{-9})	$\chi_m \gg 0, \mu_r \gg 1$
7.	Examples: Air, platinum, tungsten, potassium, aluminium, chromium, palladium, copper sulphate, manganese, etc.	Examples: Copper, gold, silver, lead, silicon, diamond, bismuth, antimony, mercury, tin, zinc, alcohol, hydrogen, nitrogen, water, etc.	Examples: Iron, steel, nickel, cobalt etc.

5.6.2 Boundary Condition for the Tangential Components

Now, we assume that the boundary carries a surface current density K normal to the plane as shown in the figure. According to boundary condition, the tangential components of magnetic field in the two media are related as

$$(H_{1t} - H_{2t}) = K$$

or

$$\left(\frac{B_{1t}}{\mu_1} - \frac{B_{2t}}{\mu_2}\right) = K$$

In vector form the boundary condition can be given as

$$(\boldsymbol{H}_1 - \boldsymbol{H}_2) \times \boldsymbol{a}_{n12} = \boldsymbol{K}$$

where, $\boldsymbol{a}_{n12}$ is the unit vector normal to the boundary directed from medium 1 to medium 2. If the media are not conductors, then the boundary is free of current, i.e., $K = 0$; and then,

$$H_{1t} = H_{2t}$$

and

$$\frac{B_{1t}}{\mu_1} = \frac{B_{2t}}{\mu_2}$$

5.6.3 Law of Refraction for Magnetic Field

For a boundary interface with no surface current, we define the law of refraction as

$$\frac{\tan\theta_1}{\mu_1} = \frac{\tan\theta_2}{\mu_2}$$

where θ_1 and θ_2 are the angles formed by the field components with the boundary interface, and μ_1, μ_2 are the magnetic permeabilities of the two different media.

5.7 MAGNETIC ENERGY

In order to establish a magnetic field around a coil, energy is required but no energy is needed to maintain it. Just as energy is stored in electrostatic field, energy is also stored in magnetic field of inductor.

5.7.1 Energy Stored in a Coil

Consider a coil with self-inductance L. If the current flowing through coil is I, then the magnetic energy stored in the coil is given by

$$W_m = \frac{1}{2}LI^2$$

5.7.2 Energy Density in a Magnetic Field

In a magnetic field with flux density $\boldsymbol{B}$, the stored magnetic energy density is given by

$$w_m = \frac{1}{2}(\boldsymbol{B} \cdot \boldsymbol{H})$$

where $\boldsymbol{H}$ is the magnetic field intensity in the region. The total magnetic energy stored in a region is obtained by taking the volume integral of the energy density, i.e.

$$W_m = \int_v w_m\,dv = \int_v \frac{1}{2}(\boldsymbol{B} \cdot \boldsymbol{H})\,dv$$

5.8 MAGNETIC CIRCUIT

If all the magnetic fluxes associated with a particular distribution of currents, is confined to a well defined path, then that can be considered as analogous to an electric circuit in steady state and refer as magnetic circuit. Figure 5.4

shows a magnetic circuit which is analogous to electric circuit. The analogy between electric and magnetic circuits is given in Table 5.3.

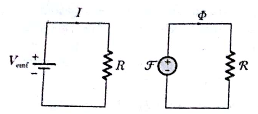

Figure 5.4: Analogy between Electric and Magnetic Circuit.

Table 5.3: Analogy between Electric and Magnetic Circuits

Electric	Magnetic
Conductivity σ	Permeability μ
Field intensity E	Field intensity H
Current $I = \int J \cdot dS$	Magnetic flux $\Phi = \int B \cdot dS$
Current density $J = \frac{I}{S} = \sigma E$	Flux density $B = \frac{\Phi}{S} = \mu H$
Electromotive force (emf) V	Magnetomotive force (mmf) $\mathcal{F}$
Resistance R	Reluctance $\mathcal{R}$
Conductance $G = \frac{1}{R}$	Permeanance $\mathcal{P} = \frac{1}{\mathcal{R}}$
Ohm's law: $R = \frac{V}{I} = \frac{l}{\sigma S}$ or $V = \int_L E \cdot dL = IR$	Ohm's law $\mathcal{R} = \frac{\mathcal{F}}{\Phi} = \frac{L}{\mu S}$ or $\mathcal{F} = \int_L H \cdot dL = \Phi\mathcal{R} = NI$
Kirchoff's Laws : $\Sigma I = 0$, $\Sigma V - \Sigma RI = 0$	Kirchhoff's Laws : $\Sigma\Phi = 0$, $\Sigma\mathcal{F} - \Sigma\mathcal{R}\Phi = 0$

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EXERCISE 5.1

MCQ 5.1.1 An electron is moving in the combined fields $E = 0.1a_x - 0.2a_y + 0.3a_z$ kV/m and $B = -3a_x + 2a_y - a_z$ Tesla. If the velocity of the electron at $t = 0$ is $V(0) = (200a_x - 300a_y - 400a_z)$ m/s then the acceleration of the electron at $t = 0$ will be
(charge on electron, $e = 1.6 \times 10^{-19}$ C; mass of electron, $m_e = 9.1 \times 10^{-31}$ kg)
(A) $1.75 \times 10^{13}(1.1a_x + 1.4a_y - 0.5a_z)$ m/s^2
(B) $2.1 \times 10^{4}(a_x + a_y - a_z)$ m/s^2
(C) $3.5 \times 10^{13}(6a_x + 6a_y - a_z)$ m/s^2
(D) $3.19 \times 10^{-17}(6a_x + 6a_y - a_z)$ m/s^2

MCQ 5.1.2 A current element of 2 m length placed along z-axis carries a current of $I = 3$ mA in the $+a_z$ direction. If a uniform magnetic flux density of $B = a_x + 3a_y$ wb/m^2 is present in the space then what will be the force on the current element in the presence of the magnetic flux density ?
(A) $6a_x - 18a_y$ mN (B) $-18a_x + 6a_y$ mN
(C) $18a_x - 6a_y$ mN (D) $-1.8a_x + 6a_y$ mN

MCQ 5.1.3 Consider two current loops C_1 and C_2 carrying current I_1 and I_2, separated by a distance R. If the force experienced by the current loop C_2 due to the current loop C_1 is F, then the force experienced by current loop C_1 due to the current loop C_2 will be
(A) $-F$ (B) F
(C) $-F\left(\frac{I_1}{I_2}\right)$ (D) $F\left(\frac{I_2}{I_1}\right)$

MCQ 5.1.4 A rectangular coil of area 1 m^2 carrying a current of 5 A lies in the plane $2x + 6y - 3z = 4$. Such that magnetic moment is directed away from origin. If the coil is surrounded by a uniform magnetic field $B = 6a_x + 4a_y + 5a_z$ wb/m^2 then the torque on the coil will be
(A) $3a_x - 20a_y - 20a_z$ N-m (B) $30a_x - 20a_y - 20a_z$ N-m
(C) $21a_x - 14a_y - 14a_z$ N-m (D) $6a_x - 4a_y - 4a_z$ N-m

MCQ 5.1.5 A circular current loop of radius 1 m is located in the plane $z = 0$ and centered at origin. What will be the torque acting on the loop in presence of magnetic field $B = 4a_x - 4a_y - 2a_z$ wb/m^2, if a uniform current of 10 A is flowing in the loop ?
(A) $20\pi(2a_x - a_y)$ (B) $40\pi(a_x + a_y)$
(C) $4\pi(a_x + a_y)$ (D) $40\pi(a_x - a_y)$

MCQ 5.1.6 Magnetic flux density inside a magnetic material is B. If the the permeability of the material is $\mu = 3\mu_0$ then the vector magnetization of the material will be
(A) $\frac{B}{3\mu_0}$ (B) $\frac{3B}{2\mu_0}$
(C) $\frac{B}{2\mu_0}$ (D) $\frac{2B}{3\mu_0}$

MCQ 5.1.7 A portion of B-H curve for a ferromagnetic material can be approximated by the analytical expression $\boldsymbol{B} = \mu_0 k\boldsymbol{H}$. The magnetization vector $\boldsymbol{M}$ inside the material is

(A) $(\mu_0 k - 1)\boldsymbol{H}$
(B) $k\boldsymbol{H}$
(C) $(k+1)\boldsymbol{H}$
(D) $(k-1)\boldsymbol{H}$

MCQ 5.1.8 A large piece of magnetic material carries a uniform magnetization $\boldsymbol{M}$ and magnetic field intensity $\boldsymbol{H}_0$ inside it. The magnetic flux density inside the material is given by

$$\boldsymbol{B}_0 = \mu_0(\boldsymbol{H}_0 + \boldsymbol{M})$$

If a small spherical cavity is hollowed out of the material then the magnetic field intensity $\boldsymbol{H}$ at the center of the cavity will be

(A) $2\boldsymbol{H}_0$
(B) $\boldsymbol{H}_0 + \frac{\boldsymbol{M}}{3}$
(C) $\boldsymbol{H}_0 - \frac{2\boldsymbol{M}}{3}$
(D) $\boldsymbol{H}_0 - \frac{\boldsymbol{M}}{3}$

Common Data For Q. 9 and 10 :

A nonuniform magnetic field $\boldsymbol{B}$ inside a medium with magnetic susceptibility $\chi_m = 2$ is given as $\boldsymbol{B} = 4z\boldsymbol{a}_z$ Tesla

MCQ 5.1.9 Bound current density inside the medium will be

(A) $\frac{3\mu_0}{8}\boldsymbol{a}_y$ A/m^2
(B) $\frac{8}{3\mu_0}\boldsymbol{a}_y$ A/m^2
(C) $\frac{4}{3\mu_0}\boldsymbol{a}_y$ A/m^2
(D) $\frac{16}{3\mu_0}\boldsymbol{a}_y$ A/m^2

MCQ 5.1.10 Total current density inside the medium will be

(A) $\frac{4}{\mu_0}\boldsymbol{a}_t$ A/m^2
(B) $\frac{4}{3\mu_0}\boldsymbol{a}_y$ A/m^2
(C) $\frac{8}{3\mu_0}\boldsymbol{a}_y$ A/m^2
(D) $4\mu_0\boldsymbol{a}_y$ A/m^2

Common Data For Q. 11 and 12 :

The two homogenous, linear and isotropic medium is defined in a Cartesian system such that medium 1 with relative permeability $\mu_{r1} = 7$ is located in the region $y \le 0$ and medium 2 with relative permeability $\mu_{r2} = 6$ is in the region $y > 0$.

MCQ 5.1.11 The magnetic field intensity in the 1st medium is $\boldsymbol{H}_1 = 9\boldsymbol{a}_x + 16\boldsymbol{a}_y - 10\boldsymbol{a}_z$. What will be the magnetic field intensity in the 2nd medium ?

(A) $9\boldsymbol{a}_x - 18.67\boldsymbol{a}_y + 10\boldsymbol{a}_z$ A/m
(B) $9\boldsymbol{a}_x + 2.63\boldsymbol{a}_y - 10\boldsymbol{a}_z$ A/m
(C) $9\boldsymbol{a}_x + 18.67\boldsymbol{a}_y - 10\boldsymbol{a}_z$ A/m
(D) $18.67\boldsymbol{a}_x - 9\boldsymbol{a}_y + 10\boldsymbol{a}_z$ A/m

MCQ 5.1.12 Magnetic flux density in medium 2 will be

(A) $(6.8\boldsymbol{a}_x - 14.1\boldsymbol{a}_y + 7.5\boldsymbol{a}_z) \times 10^{-5}$ wb/m^2
(B) $(6.8\boldsymbol{a}_x + 14.1\boldsymbol{a}_y - 7.5\boldsymbol{a}_z) \times 10^{-5}$ wb/m^2
(C) $(14.1\boldsymbol{a}_x - 6.8\boldsymbol{a}_y + 7.5\boldsymbol{a}_z) \times 10^{-5}$ wb/m^2
(D) $(54\boldsymbol{a}_x + 117\boldsymbol{a}_y - 60\boldsymbol{a}_z)$ wb/m^2

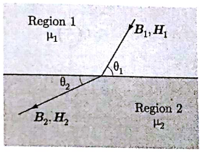
MCQ 5.1.13 The magnetic flux density in the region $z < 0$ is given as $\boldsymbol{B} = 4\boldsymbol{a}_x + 3\boldsymbol{a}_z$ Wb/m^2. If the plane $z = 0$ carries a surface current density $\boldsymbol{K} = 4\boldsymbol{a}_y$ A/m; then the magnetic flux density in the region $z > 0$ will be

(A) $4\boldsymbol{a}_x + 3(1+\mu_0)\boldsymbol{a}_z$ Wb/m^2
(B) $4\boldsymbol{a}_x + \mu_0\boldsymbol{a}_y + 3\boldsymbol{a}_z$
(C) $(4\boldsymbol{a}_x + 3\boldsymbol{a}_z)(1+\mu_0)$ Wb/m^2
(D) $4\boldsymbol{a}_x + 4\mu_0\boldsymbol{a}_y + 3\boldsymbol{a}_z$ Wb/m^2

MCQ 5.1.14 An infinite plane magnetic material slab of thickness d and relative permeability μ_r occupies the region $0 < x < d$. An uniform magnetic field $\boldsymbol{B} = B_0\boldsymbol{a}_x$ is applied in free space (outside the magnetic material). The field intensity H_{in} and flux density B_{in} inside the material will be respectively

(A) $\mu_r\mu_0 B_0$ and $\mu_r B_0$
(B) $\frac{B_0}{\mu_r\mu_0}$ and B_0
(C) $\mu_r B_0$ and $\frac{B_0}{\mu_0}$
(D) $\frac{B_0}{\mu_0}$ and $\mu_r B_0$

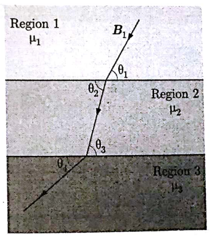
MCQ 5.1.15 In the two different mediums of permeability μ_1 and μ_2, the magnetic fields are (B_1, H_1) and (B_2, H_2) respectively as shown in the figure.



If the interface carries no current then the correct relation for the angle θ_1 and θ_2 is

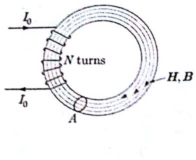
(A) $B_1\cos\theta_1 = B_2\cos\theta_2$
(B) $H_1\cos\theta_1 = H_2\cos\theta_2$
(C) $B_1\sin\theta_1 = B_1\sin\theta_2$
(D) Both (B) and (C)

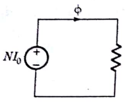
MCQ 5.1.16 In a three layer medium shown in the figure below, Magnetic flux impinges at an angle θ_1 on the interface between regions 1 and 2. The permeability of three regions are μ_1, μ_2 and μ_3. So the angle of emergence θ_4 will be independent of

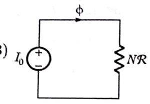


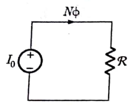
(A) μ_1 and μ_2 both
(B) μ_2 only
(C) All μ_1, μ_2 and μ_3
(D) μ_1 only

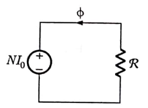
MCQ 5.1.17 The magnetic circuit shown in the figure has N turns of coil. Electrical analog for the magnetic circuit shown in the figure is



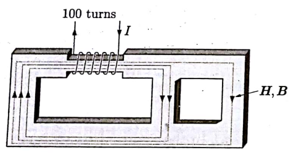
(A) 

(B) 

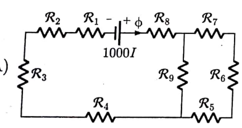
(C) 

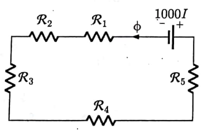
(D) 

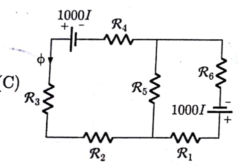
MCQ 5.1.18 The coil of the magnetic circuit shown in figure has 100 turns.

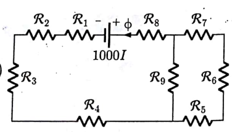


Which of the following is correct electrical analog for the magnetic circuit ?

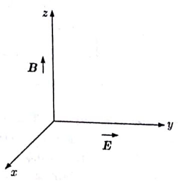
(A) 

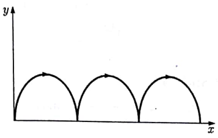
(B) 

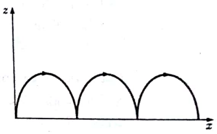
(C) 

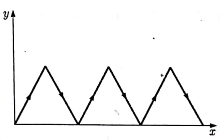
(D) 

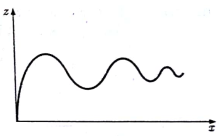
MCQ 5.1.19 In the free space the magnetic flux density $\boldsymbol{B}$ points in the $\boldsymbol{a}_z$ direction and electric field $\boldsymbol{E}$ points in the $\boldsymbol{a}_y$ direction as shown in the figure. If a charged particle at rest is released from the origin, then what path will it follow ?



(A) 

(B) 

(C) 

(D) 

MCQ 5.1.20 A point charge $+2$ C of mass $m = 6$ kg is injected with a velocity $\boldsymbol{v}_0 = 2\boldsymbol{a}_y$ m/s into the region $y > 0$, where the magnetic field is given by $\boldsymbol{B} = 3\boldsymbol{a}_z$ wb/m^2. If the point charge is located at origin at the time of injection then in the region $y > 0$ the point charge will follow

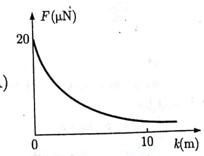
(A) a circular path centered at $(0, 0, -2)$

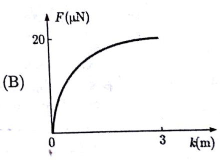
(B) an elliptical path centered at origin

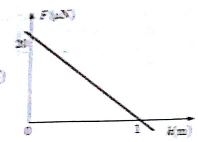
(C) a circular path centered at $(1, 2, 0)$

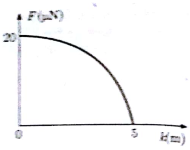
(C) a parabolic path passing through origin

MCQ 5.1.21 Two filamentary currents of $-5\boldsymbol{a}_z$ and $5\boldsymbol{a}_z$ A are located along the lines $y = 0$, $z = -1$ m and $y = 0$, $z = 1$ m respectively. If the vector force per unit length exerted on the third filamentary current of $10\boldsymbol{a}_z$ A located at $y = k$, $z = 0$ be F then the plot of F versus k will be

(A) 

(B) 

(C)


(D)


MCQ 5.1.22 A current filament placed on x-axis carries a current $I = 10$ A in $+\boldsymbol{a}_x$ direction. If a conducting current strip having surface current density $\boldsymbol{K} = 3\boldsymbol{a}_x$ A/m is located in the plane $y = 0$ between $z = 0.5$ and $z = 1.5$ m then what will be the force per unit meter on the filament exerted by the strip ?

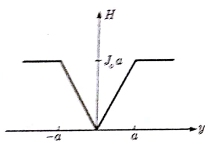
(A) $6.6\boldsymbol{a}_z$ μN/m (B) $6.6\boldsymbol{a}_z$ μN/m

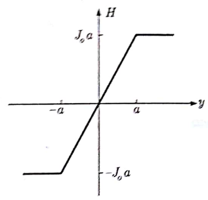
(C) $6\boldsymbol{a}_z$ μN/m (D) 0

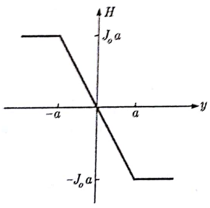
Common Data For Q. 23 and 24 :

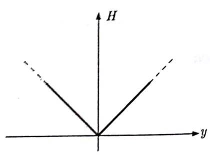
A thick slab extending from $y = -a$ to $y = +a$ carries a uniform current density $\boldsymbol{J} = J_0\boldsymbol{a}_z$

MCQ 5.1.23 Plot of magnetizing factor H at any point in the space (inside or outside slab) versus y will be

(A)


(B)


(C)


(D)


MCQ 5.1.24 If a magnetic dipole of moment $\boldsymbol{m} = m_0\boldsymbol{a}_z$ is placed at the origin then the force exerted on it due to the slab will be

(A) 0 N (B) $m_0\mu_0 J_0 y\boldsymbol{a}_z$

(C) $m_0\mu_0 J_0\boldsymbol{a}_z$ (D) $-m_0\mu_0 J_0 y\boldsymbol{a}_z$

Common Data For Q. 25 and 26 :

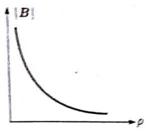
A long circular cylinder placed along z-axis carries a magnetization $\boldsymbol{M} = 5\rho^2\boldsymbol{a}_\phi$.

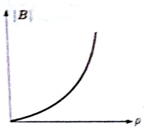
MCQ 5.1.25 The volume current density J at any point inside the cylinder is proportional to

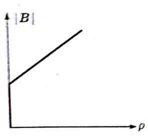
(A) ρ (B) $1/\rho$

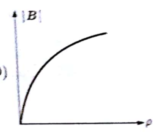
(C) $\rho\sin\phi$ (D) ρ^2

MCQ 5.1.26 The plot of the magnetic flux density B inside the cylinder versus ρ will be

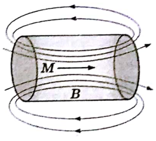
(A)


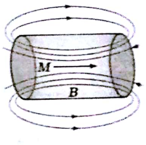
(B)


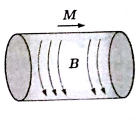
(C)


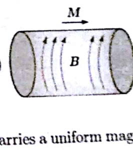
(D)


MCQ 5.1.27 Magnetization of a long circular cylinder is $\boldsymbol{M}$ along it's axis. Which of the following gives the correct pattern of magnetic field lines ($\boldsymbol{B}$).

(A)


(B)


(C)


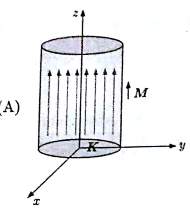
(D)


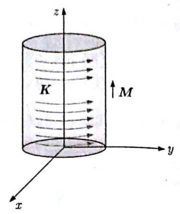
MCQ 5.1.28 Magnetic flux density $\boldsymbol{B}$ inside a sphere that carries a uniform magnetization $\boldsymbol{M}$ will be

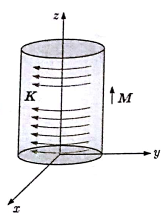
(A) 0 (B) $\frac{1}{3}\mu_0\boldsymbol{M}$

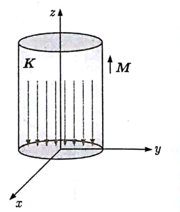
(C) $\frac{\mu_0\boldsymbol{M}}{2}$ (D) $\frac{2}{3}\mu_0\boldsymbol{M}$

MCQ 5.1.29 A short cylinder placed along z-axis carries a "frozen-in" uniform magnetization $\boldsymbol{M}$ in $+\boldsymbol{a}_z$ direction. If length of the cylinder is equal to its cross sectional diameter then pattern of its surface current density $\boldsymbol{K}$ will be as

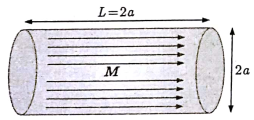
(A)


(B)


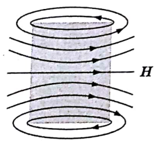
(C)


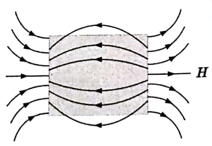
(D)


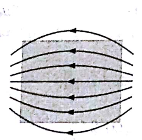
MCQ 5.1.30 A short cylinder of length equals to it's diameter carries a uniform magnetization $\boldsymbol{M}$ as shown in the figure.

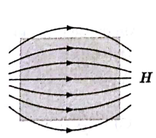


The correct sketch for the magnetic field intensity $\boldsymbol{H}$ inside the cylinder is

(A)


(B)


(C)


(D)


MCQ 5.1.31 An infinitely long straight wire of radius a, carries a uniform current I. The energy stored per unit length in the internal magnetic field will be

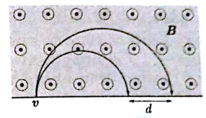
(A) uniform and depends on I only

(B) non uniform

(C) uniform and depends on a only

(D) uniform and depends on both I and a

MCQ 5.1.32 A mass spectrograph is a device for separating charged particles having different masses. Consider two particles of same charges Q but different masses m and $2m$ injected into the region of a uniform field $\boldsymbol{B}$ with a velocity $\boldsymbol{v}$ normal to the magnetic field as shown in the figure. When the particles will be releasing out of the spectrograph the separation between them will be



(A) $\frac{2mv}{Bq}$ (B) $\frac{mv}{2Bq}$

(C) $\frac{mv}{Bq}$ (D) 0

Common Data For Q. 33 and 34 :

Consider a conducting filamentary wire of length 1 meter and mass 0.3 kg oriented in east-west direction, situated in the earth's magnetic field at the magnetic equator.
(Assume the magnetic field at equator has a value of 0.6×10^{-4} Wb/m^2 and directed northward)

MCQ 5.1.33 The current that required to counteract the earth's gravitational force on the wire must flow from

(A) west to east

(B) east to west

(C) any of (A) and (B)

(D) none of these

MCQ 5.1.34 What will be the magnitude of the current flowing in the wire as to counteract the gravitational force ?

(A) 49 kA (B) 24.5 kA

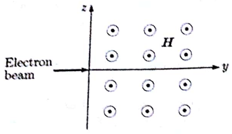
(C) 98 kA (D) 4.9 kA

MCQ 5.1.35 $\boldsymbol{B}$-$\boldsymbol{H}$ curve for a ferromagnetic material is given as $\boldsymbol{B} = 2\mu_0 H\boldsymbol{H}$. What will be the work done per unit volume in magnetizing the material from zero to a certain value $B_0 = 2\mu_0 H_0^2$?

(A) $4\mu_0 \frac{H_0^2}{3}$ (B) $4\mu_0 \frac{H_0^3}{3}$

(C) $4\mu_0 H_0^2$ (D) $2\frac{H_0^3}{3}$

MCQ 5.1.36 Electron beams are injected normally to the plane edge of a uniform magnetic field $\boldsymbol{H} = H_0 \boldsymbol{a}_x$ as shown in figure.



The path of the electrons ejected out of the field will be in

(A) $+\boldsymbol{a}_y$ direction
(B) $-\boldsymbol{a}_y$ direction
(C) $(\boldsymbol{a}_y + \boldsymbol{a}_z)$ direction
(D) $(\boldsymbol{a}_y - \boldsymbol{a}_z)$ direction

MCQ 5.1.37 Two perfectly conducting, infinite plane parallel sheets separated by a distance d carry uniformly distributed surface currents with equal and opposite densities $\boldsymbol{K}$ and $-\boldsymbol{K}$ respectively. The medium between the two plates is a magnetic material of non uniform permeability which varies linearly from a value of μ_1 near one plate to a value of μ_2 near the second plate. What will be the magnetic flux between the current sheets per unit length along the direction of flow of the current ?

(A) $\left(\frac{\mu_1+\mu_2}{2}\right)Kd$
(B) $(\mu_1+\mu_2)Kd$
(C) $\left(\frac{1}{\mu_1}+\frac{1}{\mu_2}\right)Kd$
(D) $\left(\frac{\mu_2-\mu_1}{2}\right)Kd$

Common Data For Q. 38 and 39 :

The magnetic field intensity inside an infinite plane magnetic material slab is given as $\boldsymbol{H} = 4\boldsymbol{a}_x + 2\boldsymbol{a}_y$. The permeability of the magnetic material is $\mu = 2\mu_0$

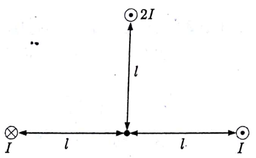
MCQ 5.1.38 If the magnetic material slab occupies the region $0 < z < 2\,\text{m}$ then the magnetization surface current densities at the surfaces $z = 0$ and $z = 2\,\text{m}$ will be respectively

(A) $(-4\boldsymbol{a}_y + 2\boldsymbol{a}_x)$ and $(4\boldsymbol{a}_y - 2\boldsymbol{a}_x)$
(B) $(-2\boldsymbol{a}_x + 4\boldsymbol{a}_y)$ and $(2\boldsymbol{a}_x - 4\boldsymbol{a}_y)$
(C) $(4\boldsymbol{a}_x + 4\boldsymbol{a}_y)$ and $(2\boldsymbol{a}_x - 4\boldsymbol{a}_y)$
(D) $(2\boldsymbol{a}_x + 4\boldsymbol{a}_y)$ and $(-2\boldsymbol{a}_x + 4\boldsymbol{a}_y)$

MCQ 5.1.39 The magnetization volume current density J_m will be

(A) 0
(B) $4\boldsymbol{a}_x + 2\boldsymbol{a}_y$
(C) $8\boldsymbol{a}_x + 4\boldsymbol{a}_y$
(D) $-4\boldsymbol{a}_x - 2\boldsymbol{a}_y$

MCQ 5.1.40 Two infinitely long straight wire and a third wire of length l are parallel to each other located as shown in the figure.



Infinitely long wire carries a current I while the wire of length l shown at the top carries a current $2I$. The magnitude of the force experienced by the top wire is

(A) $\frac{\mu I^2}{\pi}$
(B) $\mu\pi I^2$
(C) $\frac{\mu I^2}{2\pi l}$
(D) $\frac{\mu I}{2\pi l}$

MCQ 5.1.41 Medium 1 comprising the region $z > 0$ is a magnetic material with permeability $\mu_1 = 4\mu_0$ where as the medium 2, comprising the region $z < 0$ is a magnetic material with permeability $\mu_2 = 2\mu_0$. Magnetic flux density in medium 1 is given by

$$\boldsymbol{B}_1 = (0.4\boldsymbol{a}_x + 0.8\boldsymbol{a}_y + \boldsymbol{a}_z)\,\text{Wb/m}^2$$

If the boundary $z = 0$ between the two media carries a surface current of density $\boldsymbol{K}$ given by

$$\boldsymbol{K} = \frac{1}{\mu_0}(0.2\boldsymbol{a}_x - 0.4\boldsymbol{a}_y)\,\text{A/m}$$

then the magnetic flux density in medium 2 will be

(A) $(0.8\boldsymbol{a}_x + \boldsymbol{a}_y + \boldsymbol{a}_z)\,\text{Wb/m}^2$
(B) $(-\boldsymbol{a}_x + 0.8\boldsymbol{a}_y - \boldsymbol{a}_z)\,\text{Wb/m}^2$
(C) $(\boldsymbol{a}_x + 0.8\boldsymbol{a}_y + \boldsymbol{a}_z)\,\text{Wb/m}^2$
(D) $(\boldsymbol{a}_x + 0.8\boldsymbol{a}_y)\,\text{Wb/m}^2$

****

EXERCISE 5.2

QUES 5.2.1 An electron beam is passed through a uniform crossed electric and magnetic fields $\boldsymbol{E} = 15\boldsymbol{a}_y$ V/m and $\boldsymbol{B} = 3\boldsymbol{a}_z$ wb/m^2 ($\boldsymbol{E}$ and $\boldsymbol{B}$ are mutually perpendicular and both of them perpendicular to the beam). If the beam passes the field without any deflection, what will be the velocity (in m/s) of the beam ?

Common Data For Q. 2 and 3:

In the free space three uniform current sheets with surface current densities $K_1 = 4\boldsymbol{a}_x$, $K_2 = -2\boldsymbol{a}_x$, $K_3 = -2\boldsymbol{a}_x$ are located in the plane $z = 0$, $z = 1$ and $z = -1$ respectively.

QUES 5.2.2 Net magnetic field intensity produced between the sheets located at $z = 0$ and $z = 1$ will be ____ A/m in $\boldsymbol{a}_y$ direction.

QUES 5.2.3 If a conducting filament located along the line $y = 0$, $z = 0.2$ m carries 7 A current in $+\boldsymbol{a}_x$ direction then what will be the force per unit length exerted on it will be ____ $\times \mu_0 \boldsymbol{a}_z$ N/m

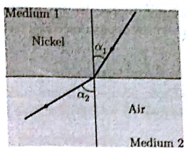
QUES 5.2.4 Magnetic flux density inside a medium is $5\boldsymbol{a}_z$ mwb/m^2. If the relative permeability of the medium is 2.3, what will be the magnetization (in A/m) inside the medium ?

QUES 5.2.5 A magnetic material of relative permeability $\mu_r = 4/\pi$ is placed in a magnetic field having strength $\boldsymbol{H} = 2\rho^2 \boldsymbol{a}_\phi$ A/m. The magnetization of the material at $\rho = 2$ will be ____ A/m in $\boldsymbol{a}_\phi$ direction.

QUES 5.2.6 A metallic bar of cross sectional area 2 m^2 is placed in a magnetizing field $H = 70$ A/m. If the field causes a total magnetic flux of $\Phi = 4.2$ mWb in the bar then the susceptibility of the bar will be ____.

QUES 5.2.7 An infinite circular cylinder is located along z-axis that carries a uniform magnetization $\boldsymbol{M} = 0.7\boldsymbol{a}_z$ A/m. The magnetic flux density due to it inside the cylinder will be ____ $\times 10^{-7} \boldsymbol{a}_\phi$.

QUES 5.2.8 Magnetic flux lines are passing from a nickel material to the free space. If the incident of the flux line makes an angle $\alpha_1 = 75°$ to the normal of the boundary in the nickel side as shown in figure then what will be the angle α_2 (in degrees) with normal of the flux when it comes out in free space ?
(relative permeability of Nickel = 600)



QUES 5.2.9 Two infinite plane conducting sheets are located in the plane $z = 0$ and $z = 2$ m. The medium between the plates is a magnetic material of uniform permeability $\mu = 4\mu_0$. If in the region between the plates a uniform magnetic flux density is defined as $\boldsymbol{B} = (3\boldsymbol{a}_x + 4\boldsymbol{a}_y) \times 10^{-3}$ Wb/m^2, what will be the magnetic energy stored per unit area (in J/m^2) of the plates ?

QUES 5.2.10 A conducting wire is bent to form a circular loop of mean radius 50 cm. If cross sectional radius of the wire is a, such that $a << 50$ cm then the internal inductance of the loop will be ____ nH.

QUES 5.2.11 A 200 turns of a coil is wound over a magnetic core of length 15 cm that has the relative permeability of 150. The current that must flow through the coil to produce 0.4 Tesla of flux density in the core is ____ Ampere.

Common Data For Q. 12 and 13 :

A filamentary conductor is formed into a rectangle such that it's corners lies on points $P(1,1,0)$, $Q(1,3,0)$, $R(4,3,0)$, $S(4,1,0)$. An infinite straight wire lying on entire x-axis carries a current of 5 A in $\boldsymbol{a}_x$ direction.

QUES 5.2.12 If the filamentary conductor carries a current of 3 A flowing in $+\boldsymbol{a}_x$ direction from Q to R then the force exerted by wire on the side QR of rectangle will be ____ $\boldsymbol{a}_y$μN.

QUES 5.2.13 The total force exerted on the conducting loop by the straight wire will be ____ $\boldsymbol{a}_y$μN.

QUES 5.2.14 A conducting current strip of 2 m length is located in the plane $x = 0$ between $y = 1$ and $y = 3$. If surface current density of the strip is $\boldsymbol{K} = 6\boldsymbol{a}_z$ A/m then the force exerted on it by a current filament placed on z-axis that carries a current $I = 10$ A in $+\boldsymbol{a}_z$ direction will be ____ μN in $\boldsymbol{a}_y$ direction.

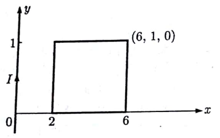
Common Data For Q. 15 and 16 :

A conducting rod of square cross section of side 2 cm carries a uniform magnetization $M = 4$ A/m along it's axis. Length of the rod is $L >> 2$ cm.

QUES 5.2.15 If the rod is bent around it into a complete circular ring then magnetic flux density inside the circular ring will be ____ $\times \mu_0$ wb/m^2

QUES 5.2.16 Assume that there remains a narrow gap of width 0.1 mm between the ends of the rod when it is formed into a circular ring. The net magnetic flux density at the center of the gap will be ____ $\times 10^{-7}$ wb/m^2

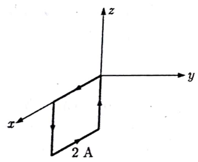
QUES 5.2.17 Mutual inductance between an infinite current filament placed along y-axis and rectangular coil of 1500 turns placed in x-y plane as shown in figure will be ____ mH.



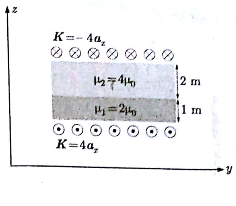
QUES 5.2.18 A planar transmission line consists of two conducting plates of 2 m width placed along x-z plane such that the current in one plate is flowing in $+\boldsymbol{a}_z$ direction. While in the other it is flowing in $-\boldsymbol{a}_z$ direction. If both the plate carries 4 A current and there is a very small separation between them then force of repulsion per meter between the two plates will be ____ $\times \mu_0 \boldsymbol{a}_y$.

QUES 5.2.19 A very long solenoid having 20,000 turns per meter. The core of solenoid is formed of iron. If the cross sectional area of solenoid is 0.04 m^2 and it carries a current $I = 100$ mA then what will be the energy stored per meter (J/m) in it's field ? (relative Permeability of iron, $\mu_r = 100$)

QUES 5.2.20 A rigid loop of wire in the form of a square is hung by pivoting one of it's side along the x-axis as shown in the figure. The loop is free to swing about it's pivoted side without friction. The mass of the wire is 0.2 kg/m and carries a current 2 A. If the wire is situated in a uniform magnetic field $\boldsymbol{B} = 1.96$ Wb/m^2 then the angle (in radian) by which the loop swings from the vertical is ____

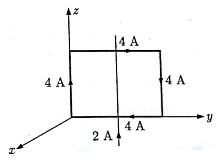


QUES 5.2.21 The medium between the two infinite plane parallel sheets carrying current densities $4\boldsymbol{a}_z$ and $-4\boldsymbol{a}_z$ A/m, consists of two magnetic material slabs of thickness 1 m and 2 m having permeabilities $\mu_1 = 2\mu_0$ and $\mu_2 = 4\mu_0$ respectively as shown in the figure. The magnetic flux per unit length between the current sheets along the direction of flow of current will be ____ $\times \mu_0 \boldsymbol{a}_y$ wb/m.

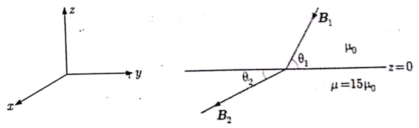


QUES 5.2.22 Two infinite plane conducting sheets lying in the plane $z = 0$ and $z = 5$ cm carry surface current densities $+20$ mA/m $\boldsymbol{a}_y$ and -20 mA/m $\boldsymbol{a}_y$ respectively. If the medium between the plates is a magnetic material of uniform permeability $\mu = 2\mu_0$ then what will be the energy stored per unit area (in J/m^2) of the plates ?

QUES 5.2.23 A square loop of a conductor lying in the yz plane is bisected by an infinitely long straight wire carrying current 2 A as shown in the figure. If the current in the square loop is 4 A then the force experienced by the loop will be ____ μN in $\boldsymbol{a}_y$ direction.



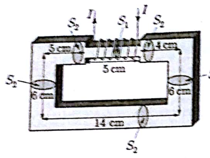
QUES 5.2.24 A certain region $z < 0$ comprises a magnetic medium with permeability $\mu = 15\mu_0$. The magnetic flux density in free space ($z > 0$) makes an angle θ_1 with the interface whereas in medium 2 flux density makes an angle θ_2 as shown in the figure. If $B_2 = 1.2\boldsymbol{a}_y + 0.8\boldsymbol{a}_z$ then what will be the angular deflection $(\theta_1 - \theta_2)$ in degrees ?



QUES 5.2.25 The coil of a magnetic circuit has 50 turns. The core of the circuit has a relative permeability of 600 and length of the core is 0.6 m. What must be the core cross section (in cm^2) of the magnetic circuit so that the coil may have a 0.2 mH inductance ?

Common Data For Q. 26 and 27 :

Consider the magnetic circuit shown in figure



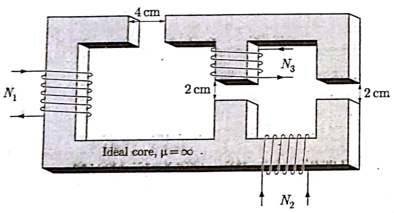
The cross sectional area of the section on which coil is wound is S_1 where as all the rest of the section has the cross sectional area S_2. Magnetic core has the permeability $\mu = 1000\mu_0$.

QUES 5.2.26 If $S_1 = 5\,\text{cm}^2$ and $S_2 = 10\,\text{cm}^2$ then the total reluctance of the circuit will be ____.

QUES 5.2.27 If the number of turn of the coil is 100 then the equivalent self inductance of the coil is ____ mH.

Common Data For Q. 28 and 29 :

A System of three coils on an ideal core is shown in figure below. The cross sectional area of all the segments of the core is $S = 100\,\text{cm}^2$.

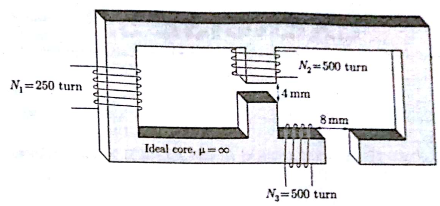


QUES 5.2.28 If $N_1 = 500$ then what will be the self inductance (in mH) of the coil having N_1 turns ?

QUES 5.2.29 If $N_2 = 250$ then the self inductance of the coil N_2 will be ____ mH.

Common Data For Q. 30 and 31 :

A system of three coils on an ideal core that has two air gaps is shown in the figure. All the segments of core has the uniform cross sectional area $2000\,\text{mm}^2$.



QUES 5.2.30 What will be the mutual inductance (in mH) between N_1 and N_2 ?

QUES 5.2.31 The mutual inductance between N_2 and N_3 will be ____ mH.

QUES 5.2.32 The magnetization curve for an iron alloy is approximately given by

$$B = \frac{1}{3}H + H^2\,\mu\text{Wb/m}^2$$

If H increases from 0 to 210 A/m, the energy stored per unit volume in the alloy is ____ MJ/m^3.

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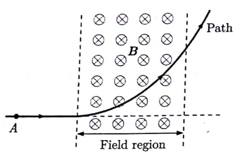
EXERCISE 5.3

MCQ 5.3.1 Path of a charged particle A that enters in a uniform magnetic field B (pointing into the page) is shown in the figure.



The deflection in the path of the particle shows that the particle is
(A) positive charged
(B) negatively charged
(C) uncharged
(D) can't be determined

MCQ 5.3.2 Unit of a magnetic point charge is
(A) Ampere meter
(B) coulomb meter
(C) Ampere meter square
(D) doesn't exit

MCQ 5.3.3 Which of the following statements is correct for a current free interface between two different magnetic media ?
(A) Normal component of magnetic field intensity will be continuous.
(B) Tangential component of magnetic flux density will be continuous.
(C) Magnetic scalar potential will be same in both the medium.
(D) None of these

MCQ 5.3.4 List I shows the type of magnetic materials and List-II shows their criterions. Match List I with List II and select the correct answer using the codes given below : (Notations have their usual meaning)

	List-I		List-II
a.	Ferromagnetic	1.	$\chi_m = 0,\ \mu_r = 1$
b.	Diamagnetic	2.	$\chi_m > 0,\ \mu_r \gtrsim 1$
c.	Non-magnetic	3.	$\chi_m < 0,\ \mu_r \lesssim 1$
d.	Paramagnetic	4.	$\chi_m >> 0,\ \mu_r >> 1$

Codes :

	a	b	c	d
(A)	2	3	1	4
(B)	4	3	1	2
(C)	4	1	3	2
(D)	1	3	4	2

MCQ 5.3.5 Which of the following is a diamagnetic material ?
(A) copper
(B) sodium
(C) carbon
(D) aluminum

MCQ 5.3.6 **Assertion (A) :** Aluminium is a paramagnetic material.
Reason (R) : A paramagnetic material have an odd no. of electrons.
(A) Both A and R are true and R is correct explanation of A.
(B) Both A and R are true but R is not the correct explanation of A.
(C) A is true but R is false.
(D) A is false but R is true.

MCQ 5.3.7 Magnetization, $\boldsymbol{M}$ is defined as
(A) $\chi_m \boldsymbol{H}$
(B) $\chi_m \mu_0 \boldsymbol{H}$
(C) $\chi_m \boldsymbol{B}$
(D) $\boldsymbol{B}/\mu_0$

MCQ 5.3.8 The unit of magnetic dipole moment is
(A) A-m
(B) A - m^2
(C) A/m
(D) C - m

MCQ 5.3.9 The dipole moment of a magnet is
(A) $Q_m \boldsymbol{d}$
(B) $Q_m \boldsymbol{d}$
(C) $Q_m I$
(D) $Q_m \boldsymbol{S}$

MCQ 5.3.10 The unit of magnetic susceptibility is
(A) Nil
(B) Amp
(C) H/m
(D) Wb

MCQ 5.3.11 The boundary conditions on $\boldsymbol{H}$ is
(A) $\boldsymbol{a}_n \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = \boldsymbol{J}_s$
(B) $\boldsymbol{a}_n \cdot (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0$
(C) $\boldsymbol{a}_n \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = \boldsymbol{J}_s$
(D) $\boldsymbol{a}_n \cdot (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0$

MCQ 5.3.12 A uniformly magnetized circular cylinder of infinite length has magnetization $\boldsymbol{M}$ along it's axis. The magnetic field intensity outside the cylinder will be
(A) non uniform
(B) uniform and depend on the radius of circular cylinder
(C) zero
(D) none of these

MCQ 5.3.13 **Assertion (A) :** Both the electric force and magnetic force are produced when a charged particle moves at a constant velocity.
Reason (R) : Electric force is an accelerating force where as magnetic force is a purely deflecting force.
(A) Both A and R are true and R is correct explanation of A.
(B) Both A and R are true but R is not the correct explanation of A.
(C) A is true but R is false.
(D) A is false but R is true.

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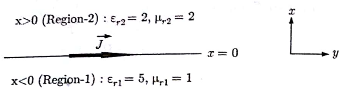
EXERCISE 5.4

MCQ 5.4.1 A current sheet $\boldsymbol{J} = 10\boldsymbol{a}_y$ A/m lies on the dielectric interface $x = 0$ between two dielectric media with $\varepsilon_{r1} = 5$, $\mu_{r1} = 1$ in Region-1 ($x < 0$) and $\varepsilon_{r2} = 2$, $\mu_{r2} = 2$ in Region-2 ($x > 0$). If the magnetic field in Region-1 at $x = 0^-$ is $\boldsymbol{H}_1 = 3\boldsymbol{a}_x + 30\boldsymbol{a}_y$ A/m the magnetic field in Region-2 at $x = 0^+$ is



(A) $\boldsymbol{H}_2 = 1.5\boldsymbol{a}_x + 30\boldsymbol{a}_y - 10\boldsymbol{a}_z$ A/m
(B) $\boldsymbol{H}_2 = 3\boldsymbol{a}_x + 30\boldsymbol{a}_y - 10\boldsymbol{a}_z$ A/m
(C) $\boldsymbol{H}_2 = 1.5\boldsymbol{a}_x + 40\boldsymbol{a}_y$ A/m
(D) $\boldsymbol{H}_2 = 3\boldsymbol{a}_x + 30\boldsymbol{a}_y + 10\boldsymbol{a}_z$ A/m

MCQ 5.4.2 A bar magnet made of steel has a magnetic moment of 2.5 A-m^2 and a mass of 6.6×10^{-3} kg. If the density of steel is 7.9×10^3 kg/m^3, the intensity of magnetization is

(A) 8.3×10^{-7} A/m (B) 3×10^6 A/m
(C) 6.3×10^{-7} A/m (D) 8.2×10^6 A/m

MCQ 5.4.3 If the current element represented by $4 \times 10^{-4}\boldsymbol{a}_y$ Amp-m is placed in a magnetic field of $\boldsymbol{H} = 5\boldsymbol{a}_x/\mu$ A/m, the force on the current element is

(A) $-2.0\boldsymbol{a}_z$mN (B) $2.0\boldsymbol{a}_z$ mN
(C) $-2.0\boldsymbol{a}_z$ N (D) $2.0\boldsymbol{a}_z$ N

MCQ 5.4.4 Match **List I** with **List II** and select the correct answer using the code given below the lists :

	List I		List II
a.	MMF	1.	Conductivity
b.	Magnetic flux	2.	Electric current
c.	Reluctance	3.	EMF
d.	Permeability	4.	Resistance

Codes :

	a	b	c	d
(A)	3	4	2	1
(B)	1	2	4	3
(C)	3	2	4	1
(D)	1	4	2	3

MCQ 5.4.5 Consider the following statements associated with boundary conditions between two media:

1. Normal component of B is continuous at the surface of discontinuity.
2. Normal component of D may or may not be continuous.

Which of the statement(s) given above is/are correct?
(A) 1 only
(B) 2 only
(C) Both 1 and 2
(D) Neither 1 nor 2

MCQ 5.4.6 Magnetic current is composed of which of the following ?
(A) Only conduction component
(B) Only displacement component
(C) Both conduction and displacement components
(D) Neither conduction component nor displacement component

MCQ 5.4.7 Which one of the following is the correct expression for torque on a loop in magnetic field $\boldsymbol{B}$? (Here $\boldsymbol{M}$ is the loop moment)
(A) $\boldsymbol{T} = \nabla \cdot \boldsymbol{B}$ (B) $\boldsymbol{T} = \boldsymbol{M} \cdot \boldsymbol{B}$
(C) $\boldsymbol{T} = \boldsymbol{M} \times \boldsymbol{B}$ (D) $\boldsymbol{T} = \boldsymbol{B} \times \boldsymbol{M}$

MCQ 5.4.8 Match List I with List II and select the correct answer using the code given below the lists :

	List-I		List-II
a.	Line charge	1.	Maxwell
b.	Magnetic flux density	2.	Poynting vector
c.	Displacement current	3.	Biot-Savart's law
d.	Power flow	4.	Gauss's law

Codes :

	a	b	c	d
(A)	1	2	4	3
(B)	4	3	1	2
(C)	1	3	4	2
(D)	4	2	1	3

MCQ 5.4.9 What does the expression $\frac{1}{2}\boldsymbol{J} \cdot \boldsymbol{A}$ represent ?
(A) Electric energy density
(B) Magnetic energy density
(C) Power density
(D) Radiation resistance

MCQ 5.4.10 Two thin parallel wires are carrying current along the same direction. The force experienced by one due to the other is
(A) Parallel to the lines
(B) Perpendicular to the lines and attractive
(C) Perpendicular to the lines and repulsive
(D) Zero

MCQ 5.4.11 A boundary separates two magnetic materials of permeability μ_1 and μ_2. The magnetic field vector in μ_1 is H_1 with a normal component H_{n1} and tangential component H_{t1} while that in μ_2 is H_2 with a normal component H_{n2} and a tangential component H_{t2}. Then the derived conditions would be

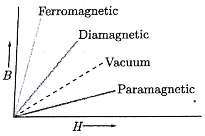
(A) $H_1 = H_2$ and $H_{t1} = H_{t2}$

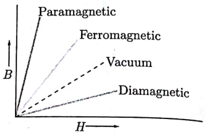
(B) $H_{t1} = H_{t2}$ and $\mu_1 H_{n1} = \mu_2 H_{n2}$

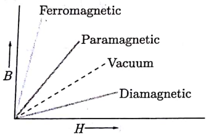
(C) $H_1 = H_2$ and $\mu_1 H_{n1} = \mu_2 H_{n2}$

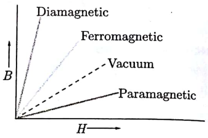
(D) $H_1 = H_2, H_{t1} = H_{t2}$ and $\mu_1 H_{n1} = \mu_2 H_{n2}$

MCQ 5.4.12 The dependence of B (flux density) on H (magnetic field intensity) for different types of material is

(A)


(B)


(C)


(B)


MCQ 5.4.13 **Statement I :** Polarization is due to the application of an electric field to dielectric materials.

Statement II : When the dipoles are created, the dielectric is said to be polarized or in a state of polarization.

(A) Both Statement (1) and Statement (2) are individually true and Statement (2) is the correct explanation of Statement (1)

(B) Both Statement (1) and Statement (2) are individually true but Statement (2) is not the correct explanation of Statement (1)

(C) Statement (1) is true but Statement (2) is false

(D) Statement (1) is false but Statement (2) is true

MCQ 5.4.14 The following equation is not valid for magneto-static field in inhomogenous magnetic materials

(A) $\nabla \cdot \boldsymbol{B} = 0$ (B) $\nabla \cdot \boldsymbol{H} = 0$

(C) $\nabla \times \boldsymbol{A} = \boldsymbol{B}$ (D) $\nabla \times \boldsymbol{H} = \boldsymbol{J}$

MCQ 5.4.15 **Assertion (A) :** Superconductors cannot be used as coils for production of strong magnetic fields.

Reason (R) : Superconductivity in a wire may be destroyed if the current in the wire exceeds a critical value.

(A) Both **Assertion (A)** and **Reason (R)** are individually true and **Reason (R)** is the correct explanation of **Assertion (A)**

(B) Both **Assertion (A)** and **Reason (R)** are individually true but **Reason (R)** is not the correct explanation of **Assertion (A)**

(C) **Assertion (A)** is true but **Reason (R)** is false

(D) **Assertion (A)** is false but **Reason (R)** is true

MCQ 5.4.16 A conductor 2 metre long lies along the z-axis with a current of 10 A in $\boldsymbol{a}_z$ direction. If the magnetic field is $\boldsymbol{B} = 0.05\boldsymbol{a}_z$ T, the force on the conductor is

(A) $4.0\boldsymbol{a}_y$ N (B) $1.0\boldsymbol{a}_z$ N

(C) $1.0\,\boldsymbol{a}_y$ N (D) $3.0\,\boldsymbol{a}_z$ N

MCQ 5.4.17 The force on a charge moving with velocity $\boldsymbol{v}$ under the influence of electric and magnetic fields is given by which one of the following ?

(A) $q(\boldsymbol{E} + \boldsymbol{B} \times \boldsymbol{v})$

(B) $q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{H})$

(C) $q(\boldsymbol{H} + \boldsymbol{v} \times \boldsymbol{E})$

(D) $q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

MCQ 5.4.18 If a very flexible wire is laid out in the shape of a hairpin with its two ends secured, what shape will the wire tend to assume if a current is passed through it ?

(A) Parabolic

(B) Straight line

(C) Circle

(D) Ellipse

MCQ 5.4.19 Consider the following :

Lorentz force $\boldsymbol{F} = e(\boldsymbol{v} \times \boldsymbol{B})$ where $e, \boldsymbol{v}$ and $\boldsymbol{B}$ are respectively the charge of the particle, velocity of the particle and flux density of uniform magnetic field. Which one of the following statements is not correct ?

(A) Acceleration is normal to the plane containing the particle path and $\boldsymbol{B}$

(B) If the direction of the particle path is normal to $\boldsymbol{B}$, the acceleration is maximum

(C) If the particle is at rest, the field will deflect the particle

(D) If the particle path is in the same direction of $\boldsymbol{B}$, there will be no acceleration

MCQ 5.4.20 What is the force on a unit charge moving with velocity $\boldsymbol{v}$ in presence of electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{B}$?

(A) $\boldsymbol{E} - \boldsymbol{v} \cdot \boldsymbol{B}$

(B) $\boldsymbol{E} + \boldsymbol{v} \cdot \boldsymbol{B}$

(C) $\boldsymbol{E} + \boldsymbol{B} \times \boldsymbol{v}$

(D) $\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}$

MCQ 5.4.21 What is the force experienced per unit length by a conductor carrying 5 A current in positive z-direction and placed in a magnetic field $\boldsymbol{B} = (3\boldsymbol{a}_x + 4\boldsymbol{a}_y)$?

(A) $15\boldsymbol{a}_x + 20\boldsymbol{a}_y$ N/m

(B) $-20\boldsymbol{a}_x + 15\boldsymbol{a}_y$ N/m

(C) $20\boldsymbol{a}_x - 15\boldsymbol{a}_y$ N/m

(D) $-20\boldsymbol{a}_x - 20\boldsymbol{a}_y$ N/m

MCQ 5.4.22 Which one of the following formulae is not correct for the boundary between two magnetic materials ?

(A) $B_{n1} = B_{n2}$

(B) $B_2 = \sqrt{B_{n2} + B_{t2}}$

(C) $H_1 = H_{n1} + H_{t1}$

(D) $a_{n21} \times (H_1 - H_2) = K$ where a_{n21} is a unit vector normal to the interface and directed from region 2 to region 1.

MCQ 5.4.23 Interface of two regions of two magnetic materials is current-free. The region 1, for which relative permeability $\mu_{r1} = 2$ is defined by $z < 0$, and region 2, $z > 0$ has $\mu_{r2} = 1$. If $B_1 = 1.2a_x + 0.8a_y + 0.4a_z$ T; then H_2 is

(A) $1/\mu_0[0.6a_x + 0.4a_y + 0.4a_z]$ A/m

(B) $1/\mu_0[1.2a_x + 0.8a_y + 0.8a_z]$ A/m

(C) $1/\mu_0[1.2a_x + 0.4a_y + 0.4a_z]$ A/m

(D) $1/\mu_0[0.6a_x + 0.4a_y + 0.8a_z]$ A/m

MCQ 5.4.24 If A and J are the vector potential and current density vectors associated with a coil, then $\int A \cdot J\,dv$ has the units of

(A) flux-linkage (B) power

(C) energy (D) inductance

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SOLUTIONS 5.1

SOL 5.1.1 Option (C) is correct.

For a moving charge Q in the presence of both electric and magnetic fields, the total force on the charge is given by

$$F = Q[E + (v \times B)]$$

where $E \rightarrow$ electric field

$v \rightarrow$ velocity of the charged particle

$B \rightarrow$ magnetic flux density

So, at time $t = 0$ total force applied on the electron is

$$F(0) = e[E + (V(0) \times B)]$$

Now we have
$$V(0) \times B = (200a_x - 300a_y - 400a_z) \times (-3a_x + 2a_y - a_z)$$
$$= 1100a_x + 1400a_y - 500a_z$$

therefore the applied force on the electron is

$$F(0) = (1.6 \times 10^{-19})[(0.1a_x - 0.2a_y + 0.3a_z) \times 10^3 + 1100a_x + 1400a_y - 500a_z]$$

$$m_e a(0) = 1.6 \times 10^{-19}[(100 + 1100)a_x + (1400 - 200)a_y + (300 - 500)a_z]$$

($F(0) = m_e a(0)$, where $a(0)$ is acceleration of electron at $t = 0$)

$$a(0) = \frac{1.6 \times 10^{-19}}{9.1 \times 10^{-31}} \times 200(6a_x + 6a_y - a_z)$$
$$= 3.5 \times 10^{13}(6a_x + 6a_y - a_z)\ \text{m/s}^2$$

SOL 5.1.2 Option (B) is correct.

Force F applied on a current element in the presence of magnetic flux density B is defined as

$$F = I(L \times B)$$

where $I \rightarrow$ current flowing in the element

$L \rightarrow$ vector length of current element in the direction of current flowing

So,
$$F = 3 \times 10^{-3}[2a_z \times (a_x + 3a_y)]$$
$$= 6 \times 10^{-3}[a_y - 3a_x] = -18a_x + 6a_y\ \text{mN}$$

SOL 5.1.3 Option (A) is correct.

The magnitude of the force experienced by either of the loops will be same but the direction will be opposite.

So the force experienced by C_1 due to C_2 will be $-F$.

SOL 5.1.4 Option (B) is correct.

Magnetic dipole moment of a coil carrying current I and having area S is given by

$$m = ISa_n$$

where a_n is normal vector to the surface of the loop.

Since the coil is lying in the plane $2x + 6y - 3z = 4$ so the unit vector normal